Scattering from Rock and Rock Outcrops

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LONG-TERM GOALS

In terms of target detection and classification, scattering from exposed rock on the seafloor, (i.e., individual rocks and rock outcrops) presents some of the most difficult challenges for modern MCM and ASW sonar systems in shallow water. Work on characterizing, modeling and simulating mean levels and other statistical measures of acoustic scattering from rocks and rock outcrops is therefore critical. Unfortunately (and curiously) information on scattering from underwater rock and outcrops is almost non-existent. Scattering from rock outcrops is not simple enough to be encompassed by a single scattering strength curve, but has a variety of expressions depending on the exact geomorphology of the rock. Smoothed surfaces may actually scatter less than surrounding sediment; curvature may dramatically affect scattering and rough areas as seen in the 'plucked' area on the rock outcrop in Fig. 1, display high variability which could pose difficulty for target detection and classification systems.

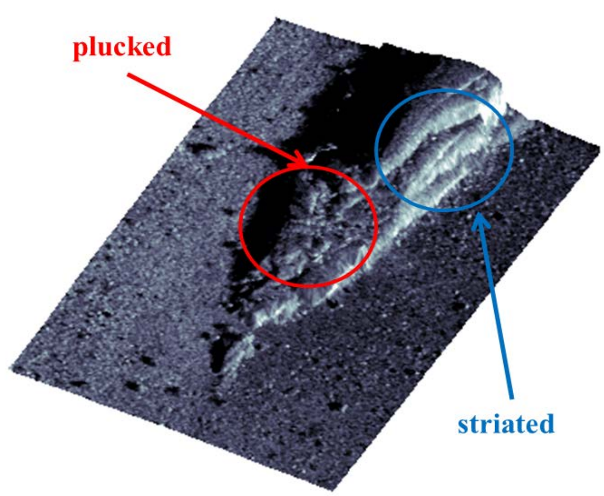

Figure 1. Combined synthetic aperture sonar image and interferometric bathymetry of a ~5rock outcrop in the Oslofjord near Larvik, Norway. The outcrop is ~5 m x 15 m.

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The primary long-term goal of this research project is to increase our understanding and modeling of high-frequency acoustic scattering from rock and rock outcrops. In addition to an increase in our basic understanding of the characteristics of scattering from rock, any resulting advances in modeling would be useful for improving simulation capabilities and for improving detection and classification tools. Inverse models based on forward models would be essential for using sonar systems for remote sensing of seafloor properties. An understanding of spatial coherence functions for isotropic and anisotropic rough seafloor surfaces could allow a method for separating natural 'target'-like objects such as rough rock from man-made targets.

OBJECTIVES

Our objectives for the proposed study of scattering from rocky seafloors and rock outcrops are intended to address many of the open questions which exist for scattering from these types of surfaces and include increasing our basic understanding of:

1) geoacoustic characteristics of rock,
2) scattering strength versus grazing angle, and
3) coherence in angle or frequency of scattering from rock.

These goals will be achieved through examination of existing literature, analysis of field data or lab measurements and by the use of extended approximate or numerical scattering models.

APPROACH

The proposed work will involve:

1) examining the literature on the morphological and geo-acoustic characteristics of various types of rock (e.g. roughness, facet size distribution, bulk properties),
2) acquiring and analyzing acoustic and environmental data collected during field tests in areas of known rock outcrops, and
3) modeling acoustic scattering by adapting existing approximate models or using numerical scattering techniques such as finite element or boundary element models.

Using broadband wide-aspect acoustic data (available, for example, from synthetic aperture sonar systems) we will characterize scattering from rock in terms of both mean levels and other statistical measures such as angular or frequency coherence and probability of false alarm (PFA). Data taken on different morphological features of rock outcrops (i.e., surfaces that are smooth, rough, curved, faceted, etc.) will be obtained and analyzed to determine the relative influence of these features on scattering characteristics such as the shape of the scattering strength versus grazing angle curves or the transition to a Lambertian shape. Environmental data consisting of high-resolution sonar measurements (such as from interferometric synthetic aperture sonar systems) taken in the experimental areas will be used as ground truth in data/model comparisons. If environmental data do not exist, we will attempt to collect it as part of this project. Data-model comparisons will yield insight into controlling factors, identify gaps in our knowledge base and highlight deficiencies in our current scattering models. Suggestions can also be made for future studies based on knowledge gained in the proposed study.

The groundwork for this study has already been laid via a variety of ongoing projects and collaborations by the PI. Through a joint ARL-PSU research project with the Norwegian Defence Research Establishment (FFI, POC Roy Hansen) and an ONR Code 33 project which ended in FY12, we took part in an at-sea experiment in Oslo Fjord where we acquired 100 kHz SAS data from FFI's HUGIN HISAS system on rocky objects over a wide range of sizes (from less than 1 m up to several 10's of m). The HISAS yields high-resolution interferometric bathymetry (~15 cm resolution) which can be used for estimating curvature and the larger-scale slope field. As part of an ongoing MCM Joint Research Program with the NATO Undersea Research Centre, we have obtained MUSCLE SAS data (300 kHz) on individual rocks and rock outcrops. To aid in the study of angular and temporal coherence we have also obtained SAS data from NURC's 'calibrated' rock with a digitized 3D shape. Additionally, as part of this research project, PhD student, Derek Olson, is exploring scattering from rock outcrops as part of his thesis work. We have also initiated joint research with NRL-DC (R. Gauss) to pass our characterization work on to them for use in lab and numerical scattering studies.

WORK COMPLETED

Over the course of FY13, work was performed by graduate student Derek Olson and the PI on modeling scattering from rocky outcrops described in the first two components listed in the technical approach described above. As virtually no information exists on scattering from rock outcrops, we have worked on obtaining relevant physical characteristics of rock outcrops, such as the roughness and morphology for use in models of acoustic scattering from rock. We compared numerical simulations to acoustic data that was collected using high-resolution acoustic data from a high-frequency imaging sonar. The sonar data analyzed this year was collected in April, 2011 during a joint field experiment that took place near Larvik, Norway, as part of a collaborative work with the Norwegian Defence Research Establishment (FFI). The SAS system operated at a center frequency of 100 kHz, has a bandwidth of 30 kHz and was operated from the HUGIN Autonomous Underwater Vehicle (AUV). A sample SAS image of a rock outcrop in the experimental area obtained with FFI's SAS system and high-resolution bathymetry of the same area can be seen in Figure 1. From the Larvik, Norway, trial, scattering strength estimates were found to range from -5 dB to -35 dB over grazing angles of 0 to 90 degrees and yielded an approximate Lambert parameter of approximately -8 (very high). The measured scattering cross section from the leeward (or 'plucked') side exhibited variability on the order of 10 dB and probability of false alarm (PFA) curves were extremely non-Rayleigh with a 'knee' in the curves suggesting two scattering mechanisms were at work as will be discussed later in this report.

Because rough rock surfaces have a very large RMS height compared to the acoustic wavelengths used in sonar systems and do not conform to typical seafloor roughness models, such as the small-slope approximations (SSA), an approximate model that will predict the scattered field is currently not feasible. Scattering behavior for these surfaces is driven by near-specular scattering from step facets, non-local shadowing by neighboring facets, diffuse scattering from convex corners and edges, and multiple scattering from concave corners of the surface. Approximate models cannot capture scattering from these types of surface features and therefore are of little use as predictive models of the statistics of scattering. Given the inadequacy of approximate models we have investigated numerical models, specifically the boundary element method (BEM) to address which of the scattering mechanisms listed above were primarily responsible for the non-Rayleigh scattering statistics.

The models discussed above require roughness parameter inputs for direct comparison to experimental measurements. To address this requirement a second field experiment was carried out in May, 2013, near the 2011 Larvik, Norway, experimental site as part of this project. Both small-scale roughness and

other features affecting acoustic scattering from rock, such as facet size were obtained. Analysis was begun on this data set in FY2013 and results will be presented below.

We are continuing discussion and coordination with researchers at NRL on their related project, “Modeling of High-Frequency Broadband False Target Phenomena” (project PIs are Roger Gauss, Dave Calvo, and Joe Fialkowski) as well as continuing the joint research project “Characterization and Modeling of Synthetic Aperture Sonar Data,” with FFI (POC - Roy Hansen)

RESULTS

From the Larvik, Norway, trial, scattering strength from rocks was extracted from the normalized pressure squared by selecting a region and averaging in cross-range, and then averaging over one degree increments. To measure the scattering strength from a rock surface, the mean slope was determined from high-resolution interferometric bathymetry so that the global grazing angle of the ideal mean seafloor could be mapped to the local grazing angle of the rock. After system calibration, scattering strengths were found to range from -5 dB to -35 dB over grazing angles of 0 to 90 degrees. The plot in Fig. 2 displays sample scattering strength data taken from the rough (‘plucked’) portion of a granite rock outcrop.

Surfaces resulting from glacial quarrying are composed of steps whose orientations and size distributions reflect the internal fault organization of the bedrock. A mathematical model of the leeward side of an outcrop can be generated to use in numerical simulations of acoustic scattering. Random stepped profiles can be simulated by generating horizontal and vertical segments, each with their own size distribution, then connecting them together. This surface model's input parameters are functions of the distributions of both the vertical and horizontal segments, and their appropriate parameters. The exponential distribution has been shown to describe field measurements of block size distribution in bedrock.

The BEM solves the Helmholtz-Kirchhoff Integral Equation (HKIE) by discretizing the boundary of a surface, and converting the integral equation into a matrix equation. In this research the boundary and surface pressure were described by piece-wise continuous linear elements whose endpoints are the nodes of the surface. At each node, the pressure depends on the pressure integrated over all other elements. If the HKIE is formulated at each point, then a linear system of equations can be formulated, and solved for the pressure, or its normal derivative, at each node and element. The resultant surface pressure and its normal derivative are then propagated to field points within the homogeneous medium. From this pressure at a field point, scattering strength can be computed as well as PFA for various values of kh and kL (mean vertical and horizontal facet scales times the acoustic wavenumber). To estimate the PFA, a histogram of the pressure amplitude at each angle, normalized by its variance is formed. The histogram is normalized by its discrete integral, and then converted to CDF by taking the normalized cumulative sum. The plot in Fig. 2 displays a set of BEM derived scattering strength curves for the facet surface model with varying kL and a fixed kh of 4. Predictions are close to the levels seen with in real data and are roughly Lambertian in shape, which was also seen in the real data. The left plot in Fig. 3 displays experimentally determined PFA for the same surfaces and is clearly non-Rayleigh. The PFAs exhibit a concave curvature in log-linear space (a ‘knee’), which is not possible with the K-distribution and is suggestive of that the data may require a combination of mechanisms (or mixture model) to fit the curve. The two mechanisms contributing could be scattering from small scale roughness combined with specular scattering from facets oriented close to normal incidence to the sonar system. Diffraction from sharp edges may also contribute strong scattering that

is non-directional as for scattering from small scale roughness. The large number of specular points provided by the large roughness causes a large number of high-amplitude events skewing the ‘tail’ of the distribution. A mixture model consisting of Rayleigh and K would be a good candidate to fit PFA from this two-component scattering surface.

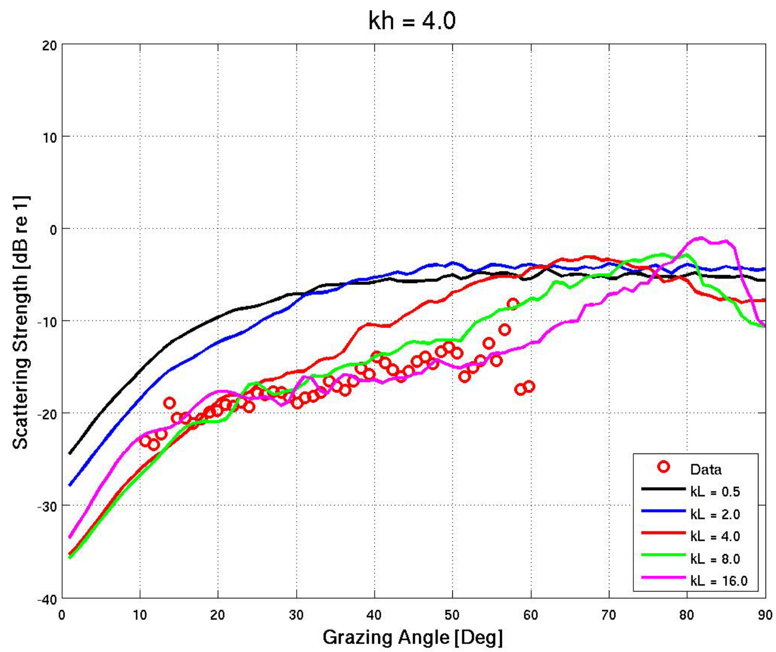

Figure 2. Scattering strength of rock outcrop at 100 kHz obtained from FFI’s HUGIN HISAS imaging sonar (circles) and estimates of scattering strength obtained from BEM simulations with a facet model used for the rough surface (lines).

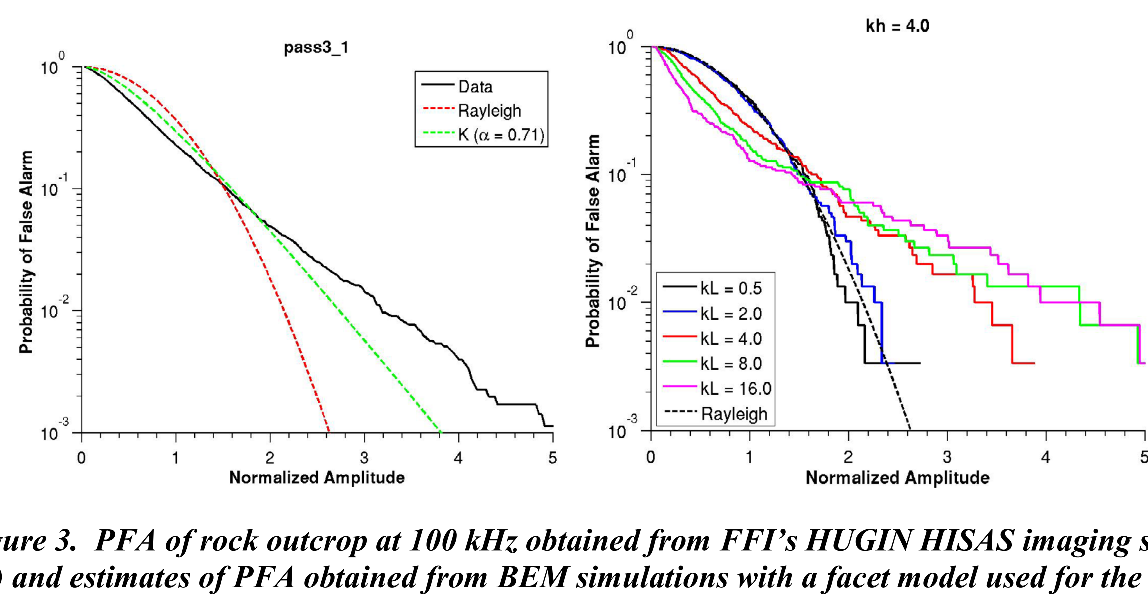

Figure 3. PFA of rock outcrop at 100 kHz obtained from FFI’s HUGIN HISAS imaging sonar (left) and estimates of PFA obtained from BEM simulations with a facet model used for the rough surface (right).

Examination of the surface pressure distribution computed by the BEM can reveal clues to the dominant features responsible for the trends observed in the cross section and PFA curves. An examples of the surface pressure distribution for kh = 4.0 are displayed in Fig. 4. The incident pressure is directed from the upper left corner, towards the lower right corner at 45° (note that the vertical scale is exaggerated). In both plots, the facets facing towards the incoming wave have higher amplitude than facets pointing away. For certain facets, the maximum pressure amplitude is near the center of the facet, whereas for others, it is at the edge, near a corner. It is hypothesized that for facets with a maximum near the center, the dominant process is that of specular scattering from planar segments. For segments with the maximum near the corner, diffractions from the corner dominate. The determination of whether corner diffraction or specular scattering dominates a given facet is not clear, and may depend on its size, and relative position to other corners of the surface. Non-local occlusion may also be responsible for decreasing the amplitude of the surface pressure on a facet. True parameters for use in the surface model used in this research have been collected in a recent field experiment and are currently being analyzed. Figure 5 shows PhD student Derek Olson alongside the photogrammetry system of his design preparing to make rock roughness measurements near the Larvik, Norway, 2011 experimental site. Figure 6 shows a sample of ground truth collected on the types of structures causing the scattering characteristics seen in Figs. 2 and 3. The left photos in the figure show one image of a stereo pair collected on the rough or 'plucked' side of a glacially formed rock outcrop. The right images are the height distribution calculated using both images in the stereo pair. Over the next year these height distributions will be used as input to models to make predictions of mean scattered levels and PFA for direct comparison to measured data.

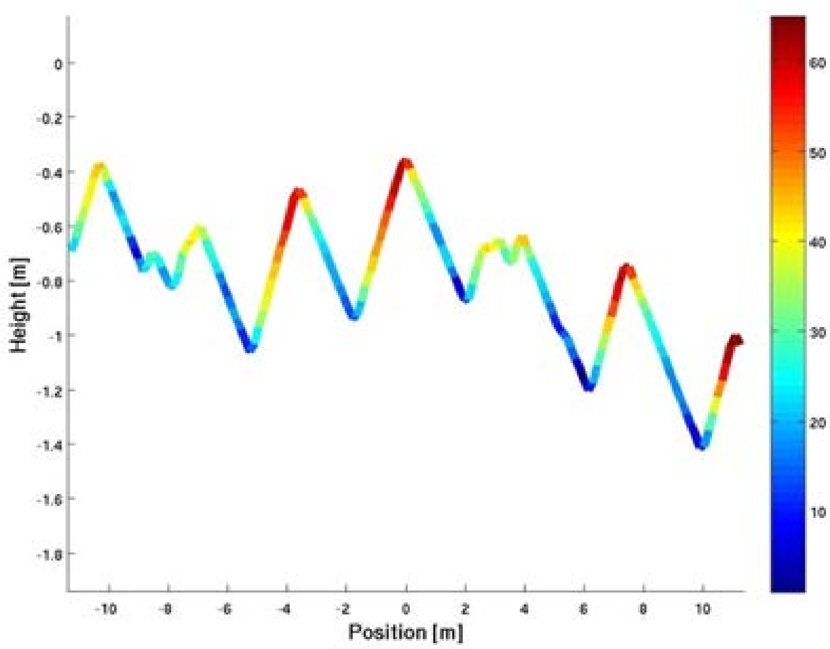

Figure 4. Example of the surface pressure distribution for kh = KL = 4.0.

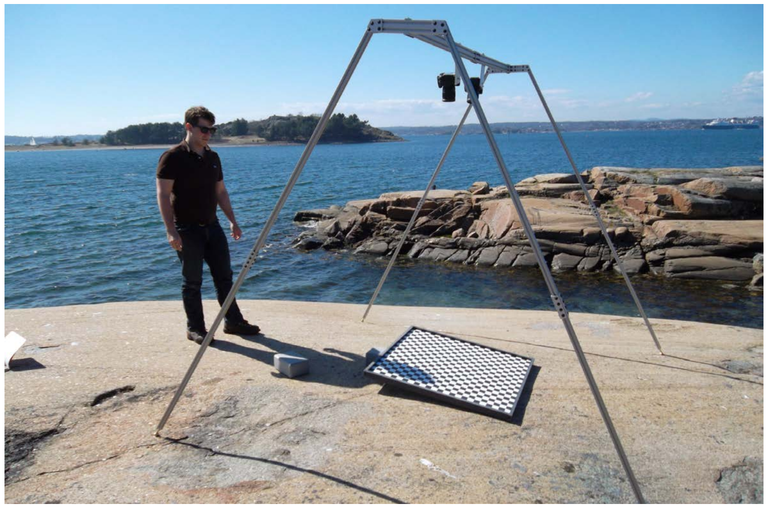

Figure 5. Stereo photogrammetry system used for ground truth roughness measurements.

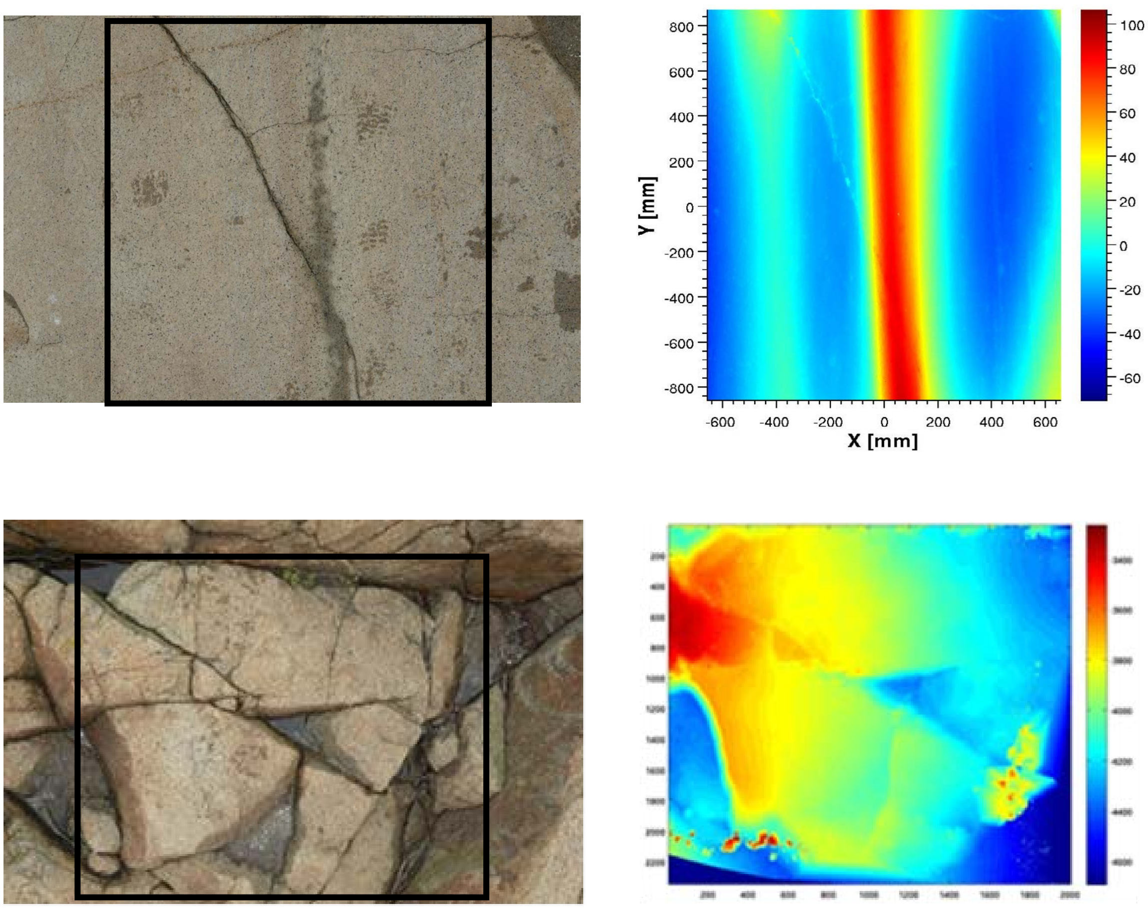

Figure 6. Images taken with the stereo-photogrammetry system (left) and estimates of high-resolution roughness taken near Larvik, Norway (right).

IMPACT/APPLICATIONS

The primary work completed over the course of this project consisted of developing techniques for modeling scattering from rough rock outcrop areas and comparing results with acoustic data sets collected from rocky areas. The proposed project was designed to increase our understanding of and simulation capability for acoustic scattering from rock outcrops. This study is yielding useful knowledge of rock outcrops as a mechanism responsible for shallow water false alarms and how levels of false alarm relate to physical properties and features of rock outcrops. Guidance relevant to this false alarm mechanism is being provided to researchers at the Naval Research Laboratory and will also be provided to those developing digital simulation content for the Guidance and Control (D&I) Modeling and Simulation TEAMS Initiative. Other deliverables are journal articles that are in preparation based on the conference presentations listed below.

RELATED PROJECTS

None.

PUBLICATIONS

Lyons, A.P., D.C. Brown, D.R. Olson and S.F. Johnson, 2013, Seafloor measurements using synthetic aperture sonar, Proceedings of Meetings on Acoustics, Vol. 19, 070002, DOI: 10.1121/1.4800729.

Olson, D.R. and A.P. Lyons, 2013, The impact of finite ensonified area on the scattering cross section, Proceedings of Meetings on Acoustics, Vol. 19, 070012, DOI: 10.1121/1.4800713.

Olson, D.R. and A.P. Lyons, 2013, Numerical simulation of high-frequency acoustic scattering from very rough glacially-plucked surfaces using the boundary element method, Proceedings of the 1st Underwater Acoustics conference, Corfu, Greece eds. John S. Papadakis and Leif Bjorno.